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NUCLEAR POWER IN SPACE

past, current & future

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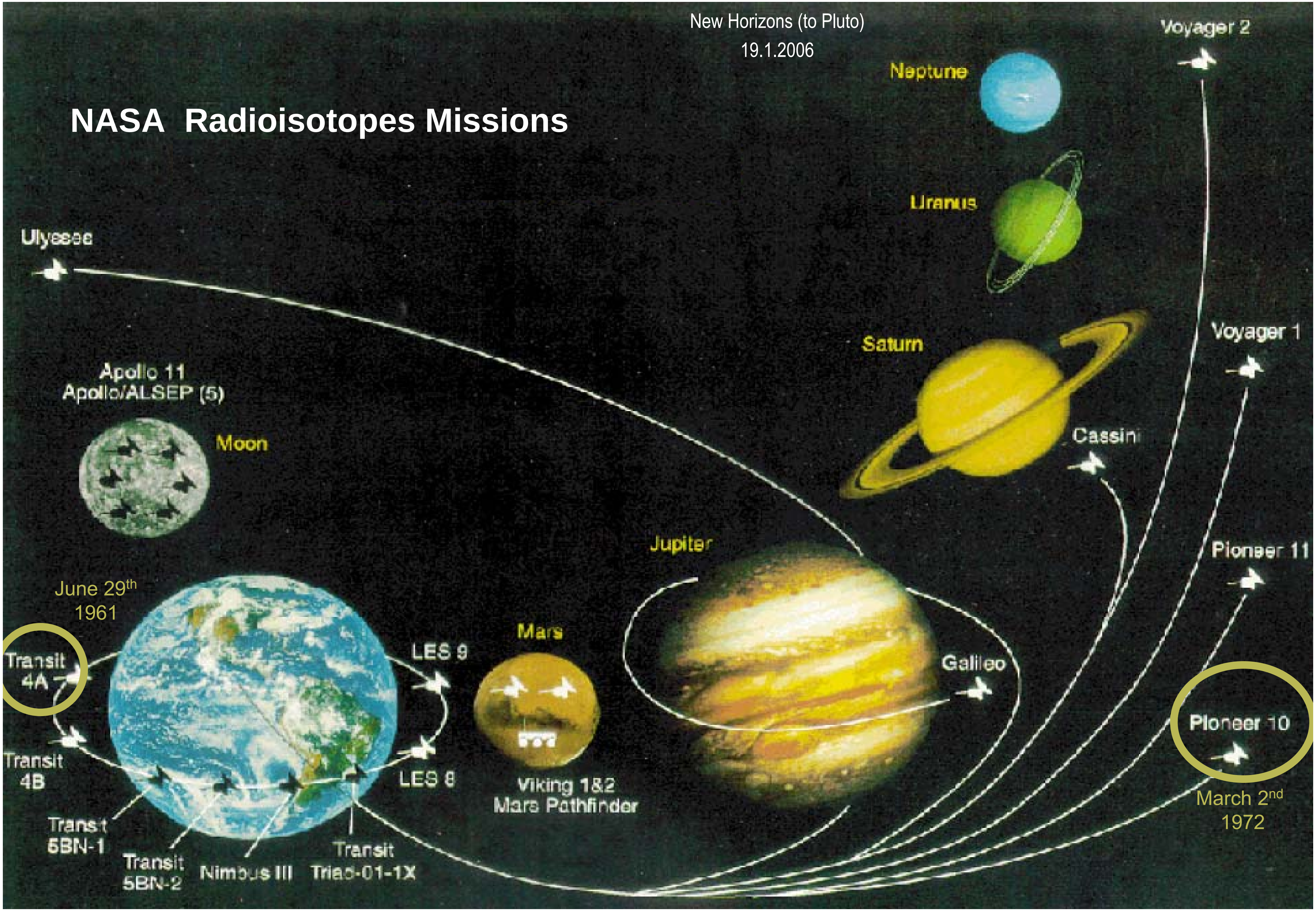
Presentation Outline

- Nuclear technology & Space exploration
  - Two completely different technologies? Or not!
- Why, when, where?
  - Short introduction and historical review
- Nuclear energy: heat and electricity source
  - RTG
- Nuclear energy: propulsion and electricity generator
  - NTR

- Examples, Case studies, and Exercises

NASA Radioisotopes Missions



Why nuclear energy in space?

- Energy requirements of all space missions are significant
  - Acceleration and de-acceleration
  - Stabilisation and guidance
  - Power supply for communication and other electronic systems
  - For heating of vital systems (and sometimes cooling)
  - Power supply for scientific experiments and equipment
  - Manned missions require significant amounts of energy
    - Air conditioning, cooling, heating, liquid processing, …
- At smallest possible mass!

Why nuclear energy in space?

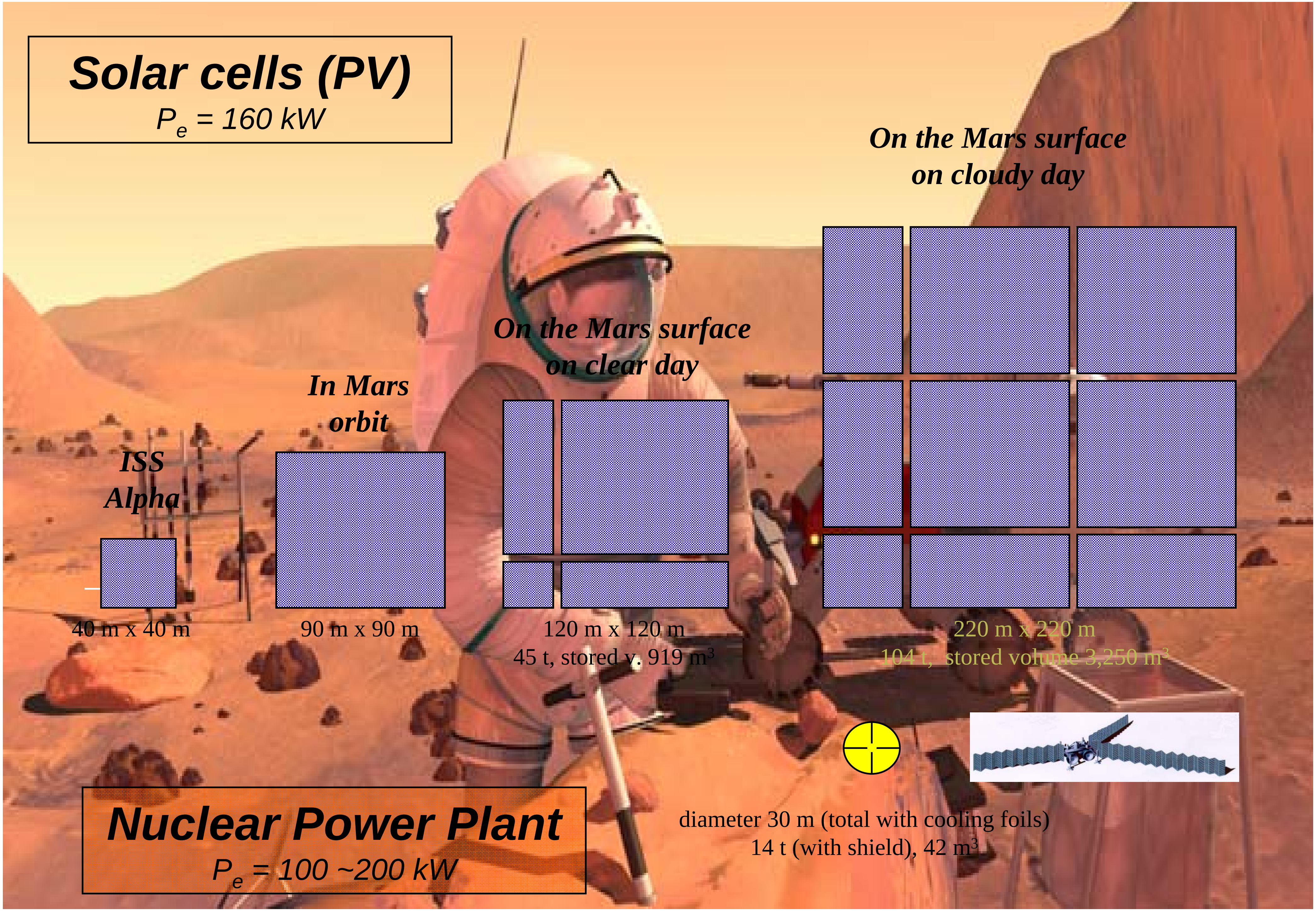
- Fuel mass (batteries, fuel cells mass) is a significant constraint for space missions.

- Solar irradiation – abundant energy source in the space

- Is solar irradiation “free” – no need for fuel supply?
  - Mass of photovoltaic (PV) solar panels

- Solar power decreases with distance from the sun

$$P_{solar} \sim 1/r^2$$



Solar cells (PV)
Pe = 160 kW
On the Mars surface
on cloudy day
On the Mars surface
on clear day
In Mars
orbit
ISS
Alpha
40 m x 40 m
90 m x 90 m
120 m x 120 m
45 t, stored v. 919 m3
220 m x 220 m
104 t, stored volume 3,250 m3
Nuclear Power Plant
Pe = 100 ~200 kW
diameter 30 m (total with cooling foils)
14 t (with shield), 42 m3

Why nuclear energy in space?

- Solar energy
  - Most efficient close to sun and for limited power requirements (up to 50 kW)
  - If we travel further away we must carry our energy “with us”
- Chemical energy – energy stored in fuels and bateries
  - ≈eV per one reaction
- Nuclear energy – energy released in nuclear reactions
  - Nuclear energy can be released during
    - Radioactive decay
    - Fission
    - (Fusion)
  - ≈ MeV per one reaction
- The difference between the specific energy stored in nuclear and chemical fuels is six orders of magnitude!

Case study

Cassini mission: Heating and electricity requirements

- Cassini requires 600 to 700 W at Saturn
- 1600 billion km from Sun
- For 11 years after mission start

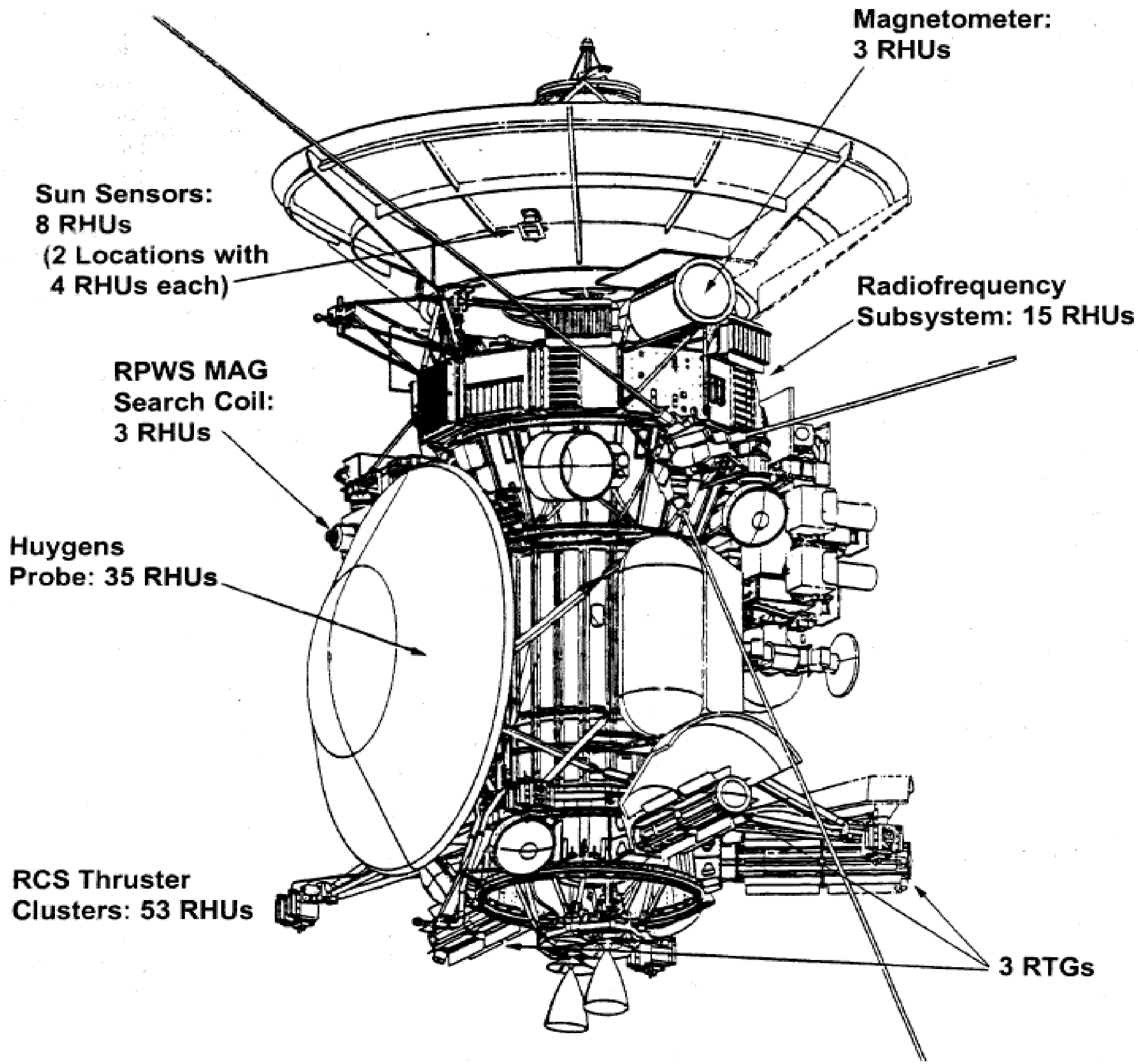
Solar cells (PV)

- 1337 kg
- 598 m^2
- - no such launch vehicle
- - manoeuvring problems (large mass)
- + no radioactivity

Nuclear source

- 168 kg
- + small (1,1 m x 0,3 m)
- - public opinion ?

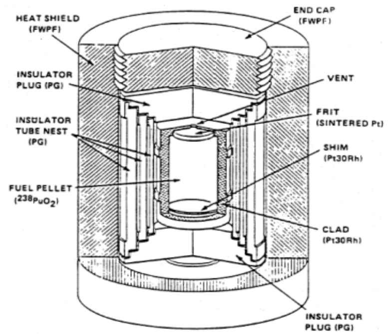
Location of Radioisotope Heater Units (RHUs) and Radioisotope Thermoelectric Generators (RTGs)



Radioisotope Energy Sources on Cassini

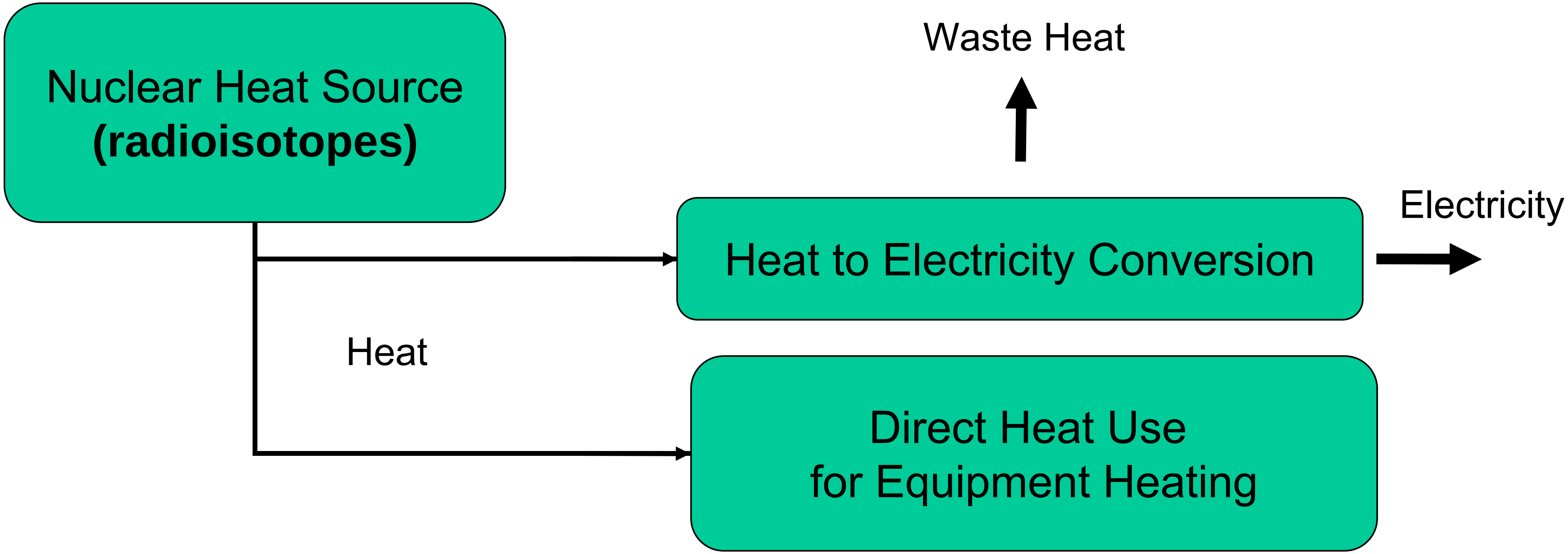
- 3 RTG units for electricity supply
  - RTG – Radioisotope Thermoelectric Generator
  - 23,2 kg ^{238}Pu

- 157 RHU units heats up vital systems and components
  - RHU – Radioisotope Heater Unit
  - 300 g ^{238}Pu



Radioisotope Heater Unit (RHU)

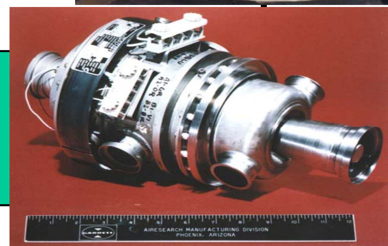
General Concept of Nuclear Energy Source



Heat to Electricity Conversion

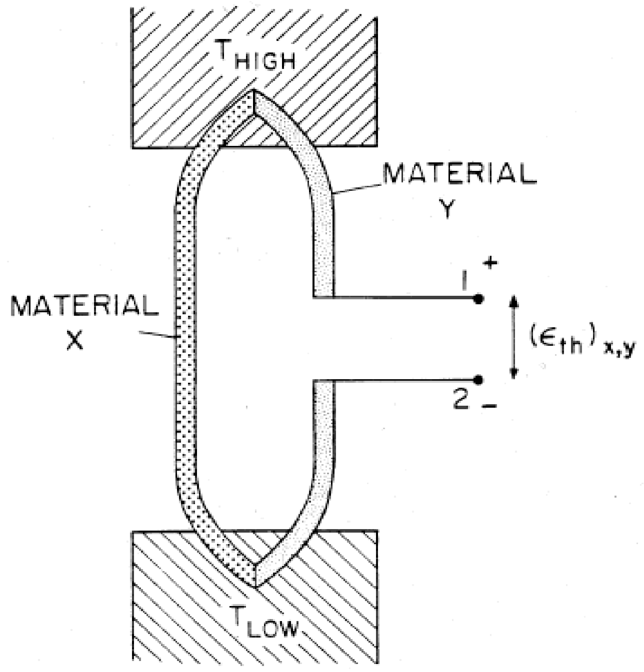
Heat Source

- Static Processes
  - Thermoelectric converter
  - Thermionic converter
- Dinamic Processes
  - Rankine
  - Brayton
  - Stirling



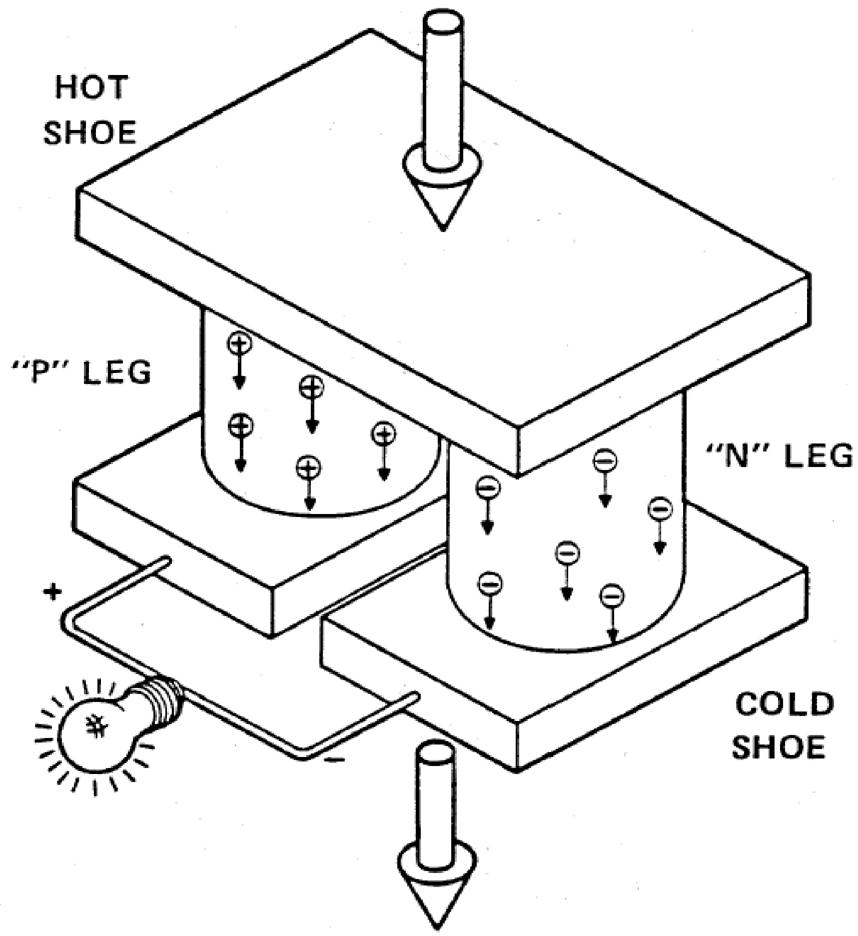
Thermoelectric Generator (TG)

- Based on Seebeck effect (1822)
- When two dissimilar conductors, X & Y, constitute a circuit, a current will flow as long as the junctions of the two conductors are at different temperatures.
- Seebeck coefficient :
  - $\alpha_{xy}(T) = dU/dT$
  - $U = \alpha\,(T_h - T_l)$
- Typical values:
  - α_{metal} ≈ 5 μV/K
  - $\alpha_{semiconductor}$ ≈ 200 μV/K
  - $\alpha_{insulator}$ ≈ 1000 μV/K



Thermoelectric Generator (TG)

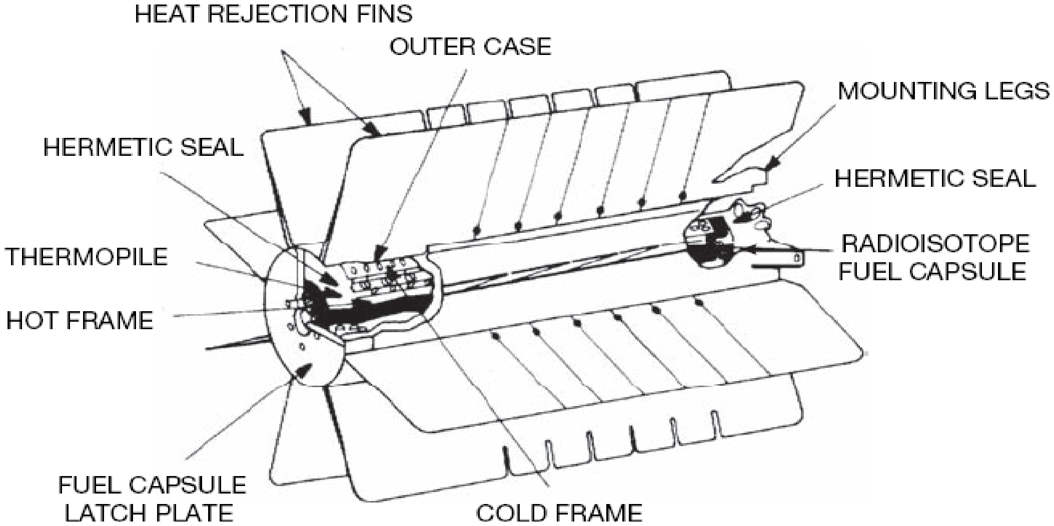
- Ideal TG material would be:
  - Good electric conductor, it would have low resistance (low internal resistance – small losses)
  - Poor heat conductor, it would create large T differences between hot and cold leg
  - High Seebeck coefficient
- A material with these conditions is hard to find, the closest are semiconductors (Si-Ge)
- TG efficiencies are really small
  - Between 1 and 2 %



Source: G. Kulcinski, University of Wisconsin

RTG Example: SNAP-27

Photo: T. Žagar

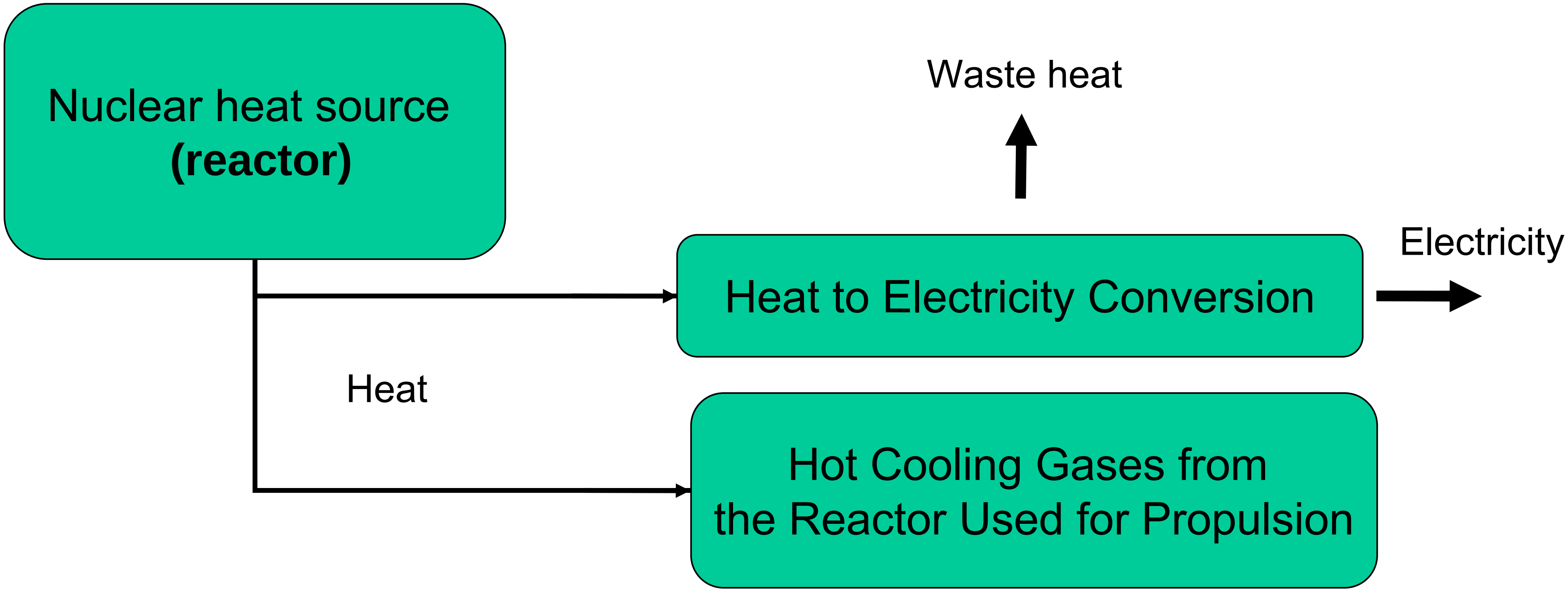


Apollo 12 mission (NASA, 1969) used five SNAP-27 RTG units to power different experiments on the surface of the Moon.

Comparison of ^{238}Pu With Other Radioisotopes

Isotope (material)	Class of Emitter	Half-Life [let]	Density [g/cm^3]	Specific Power [W/g]	Melting Temp. [°C]	Pb Shield Required [in.]
^{238}Pu (PuO_2)	α	88	10.0	0.42	2402	0.1
^{241}Am (AmO_2)	α	432	10.5	0.10	2000	0.7
^{137}Cs (CsCl)	β, γ	30	3.2	0.12	645	4.6
^{60}Co (metal)	γ	5.3	8.8	1.74	1495	9.5

Nuclear Reactor as a Heat Source



Why reactor as a heat source?

Fission of 1 kg ^{235}U releases

500 000 times

more energy,

compared to radioactive decay of

1 kg ^{238}Pu in 10 years.

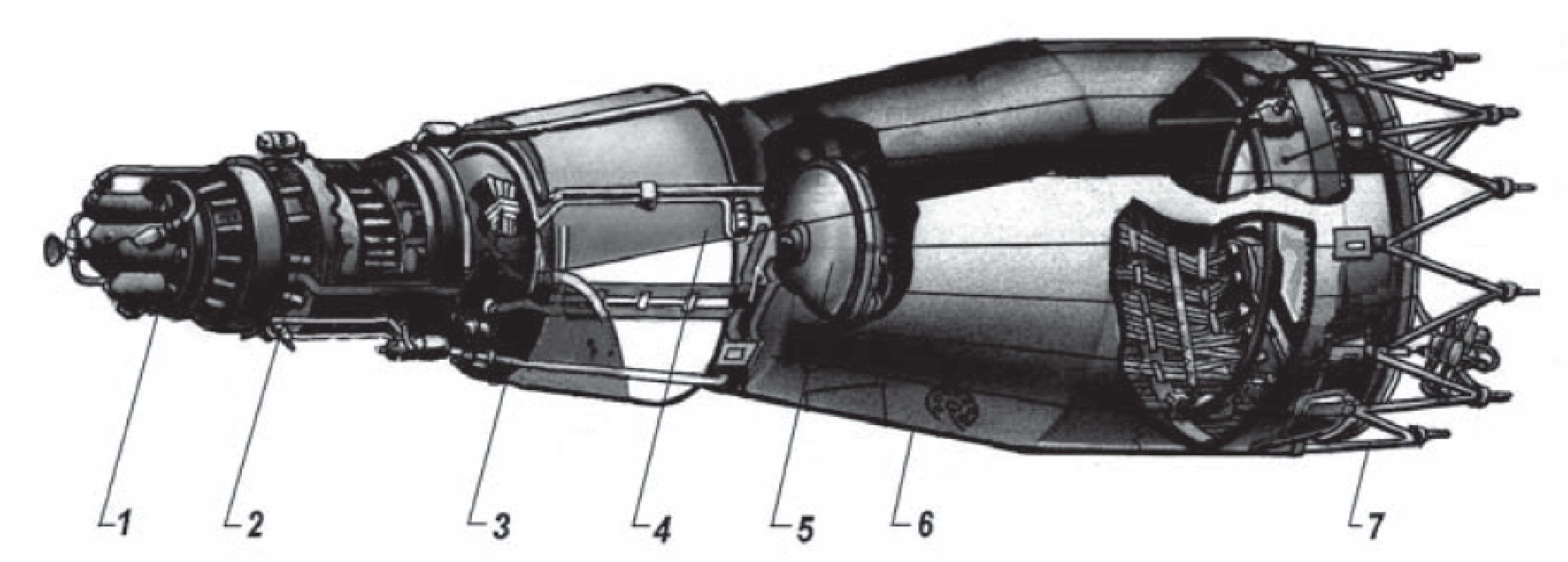
Example: SNAP-8 (from the 60')

- SNAP-8
  - Reactor cooled with liquid NaK (900 K)
  - Generator was powered by Rankin turbine adopted for liquid NaK coolant
  - Efficiency was 8 %
  - System operated at 35 kWe
  - This model operated succesfully for more than 7000 hours (on ground)
  - This model was never used in orbit
- SNAP-10A
  - Reactor based power unit
  - Thermoelectric heat to electricity conversion
  - Operated for 43 days in orbit

Source: R. Cataldo, NASA Glenn Research Center

Example: Soviet TOPAZ reactor

- In 1987 Soviet Union launched two Plasma-A satellites with TOPAZ reactors
- Operated for approx. one year delivering 6 kWe
- Reactor power was approx. 100 kW
- Efficiency of thermionic converter was 5.5 %



Source: STI/PPUB/1197, IAEA

Nuclear Energy for Propulsion?

1 kg of fissionable material (^{235}U) contains

10 000 000 times

more energy,

as 1 kg of chemical fuel.

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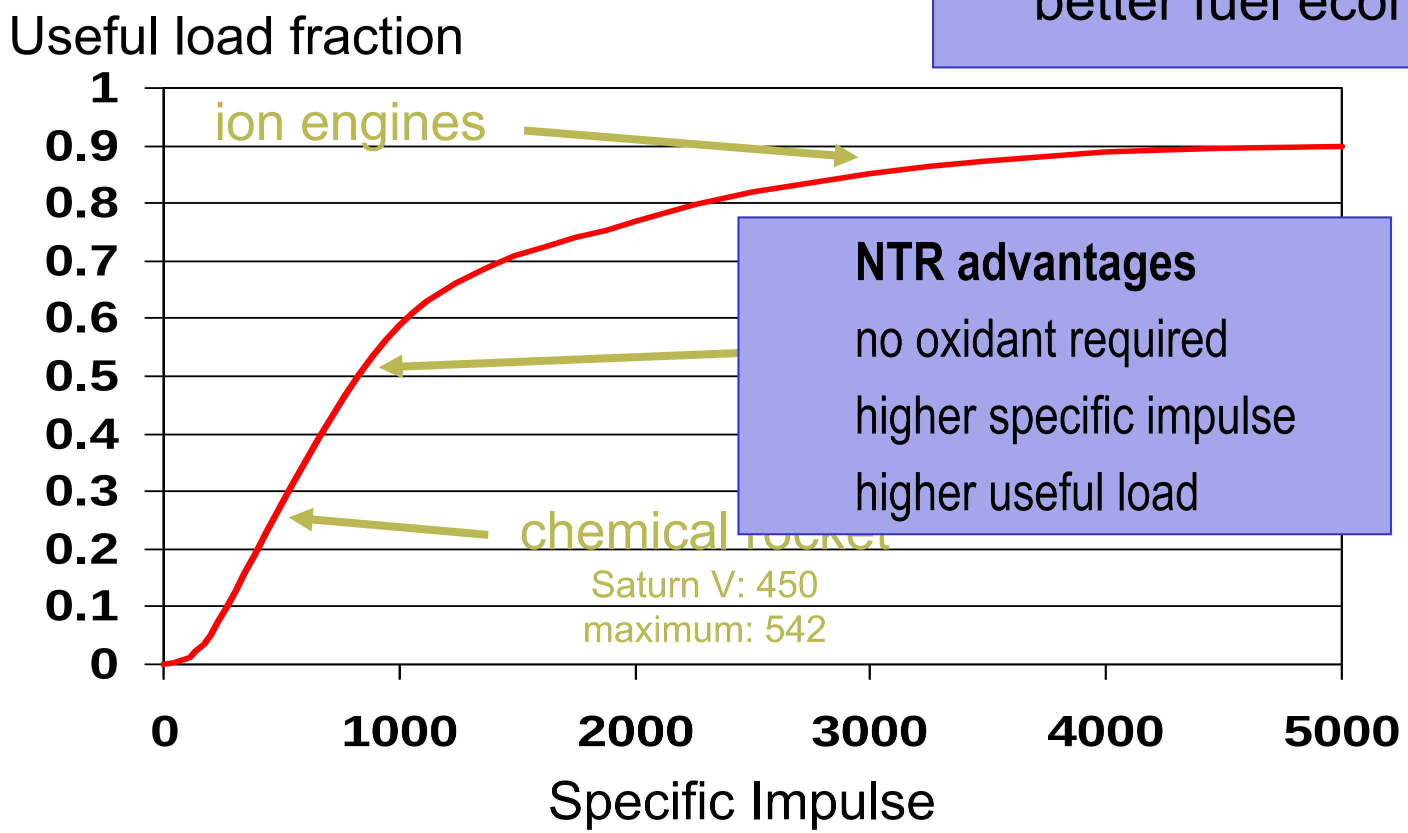
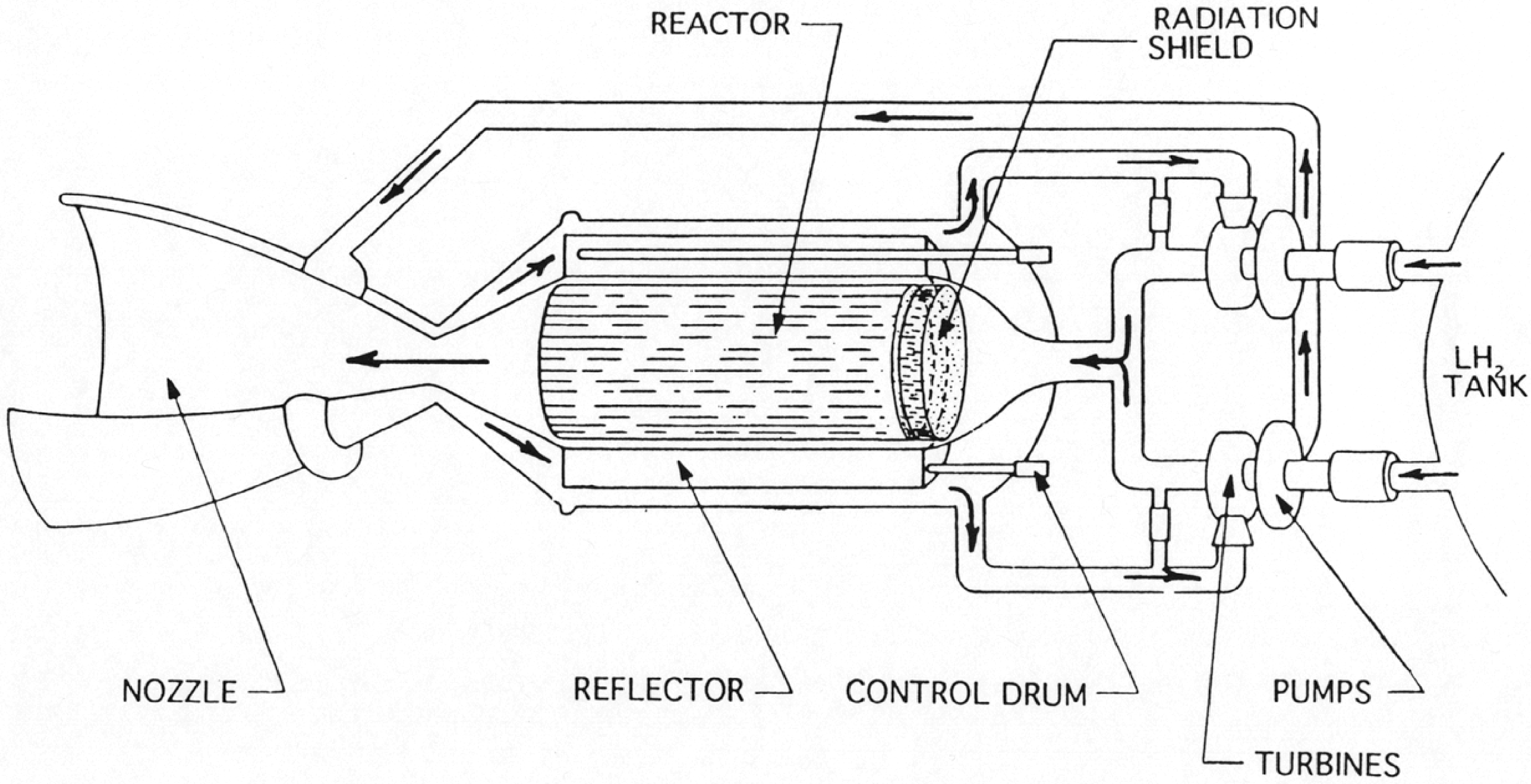
Useful Load Fraction

- Higher specific impulse - higher useful load fraction
  - Specific impulse for rocket engines is proportional to average exhaust speed

Higher specific impulse
better fuel economy ☺



Solid Core Nuclear Thermal Rocket (NTR)

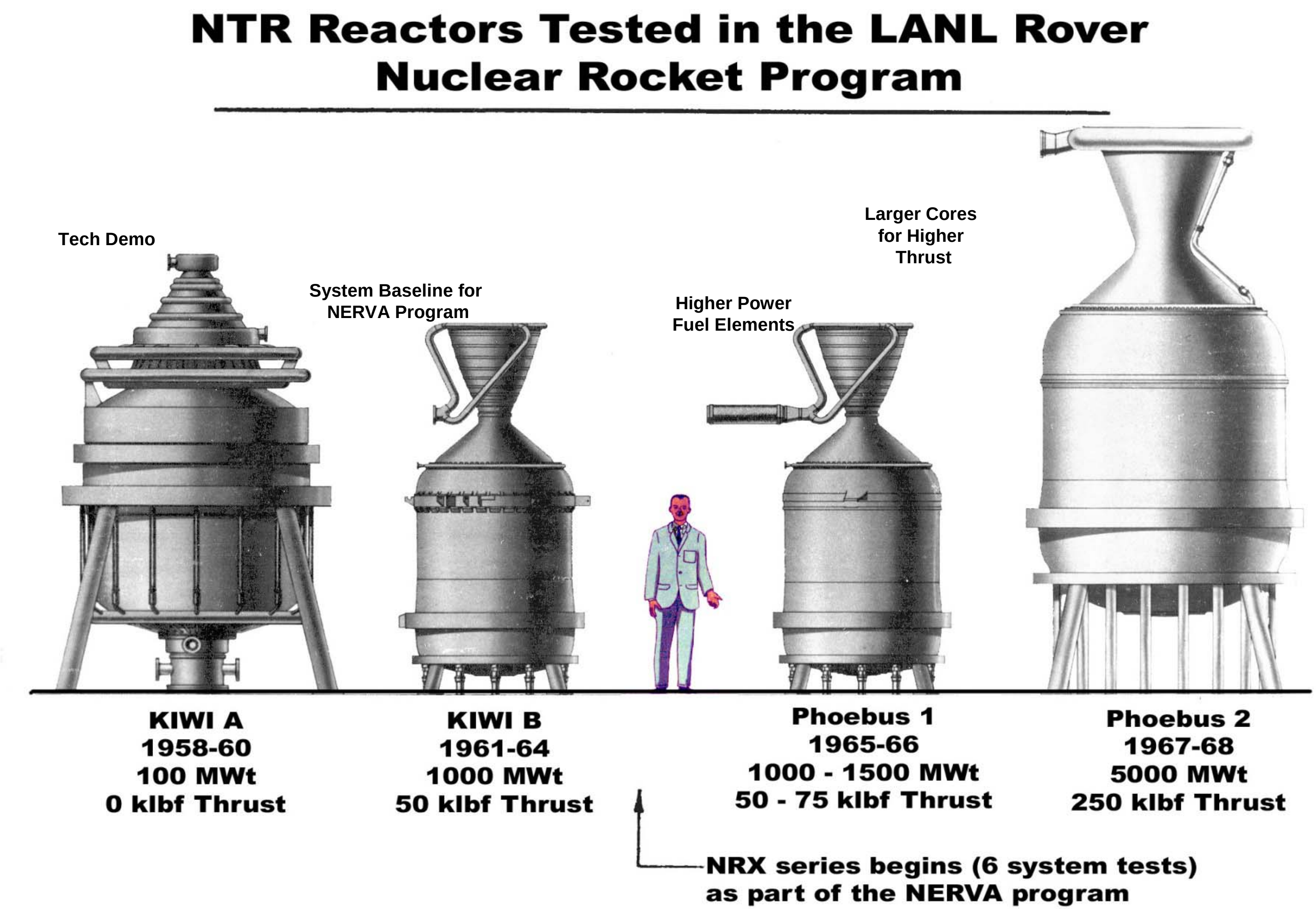


Source: S. Borowski, NASA Glenn Research Center, Cleveland, Ohio

Concept Illustration

NEPA – Nuclear Energy for Propulsion of Aircraft (1948), ANP – Aircraft Nuclear Propulsion (1950/51 – 1961)
Heat Transfer Experiment No. 1 (1955) in No. 2 (1957)
Area North, Idaho, USA

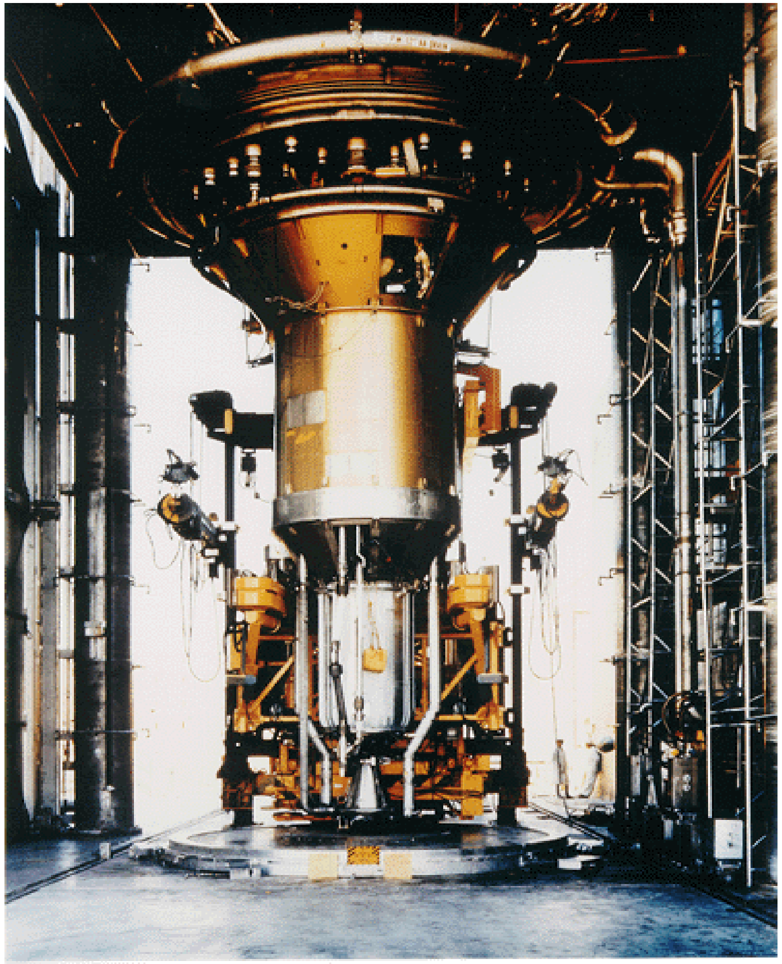
Nuclear Thermal Rocket Development 1955 – 1972



NERVA: Nuclear Engine for Rocket Vehicle Applications

Rover / NERVA Program Summary 1959-1972

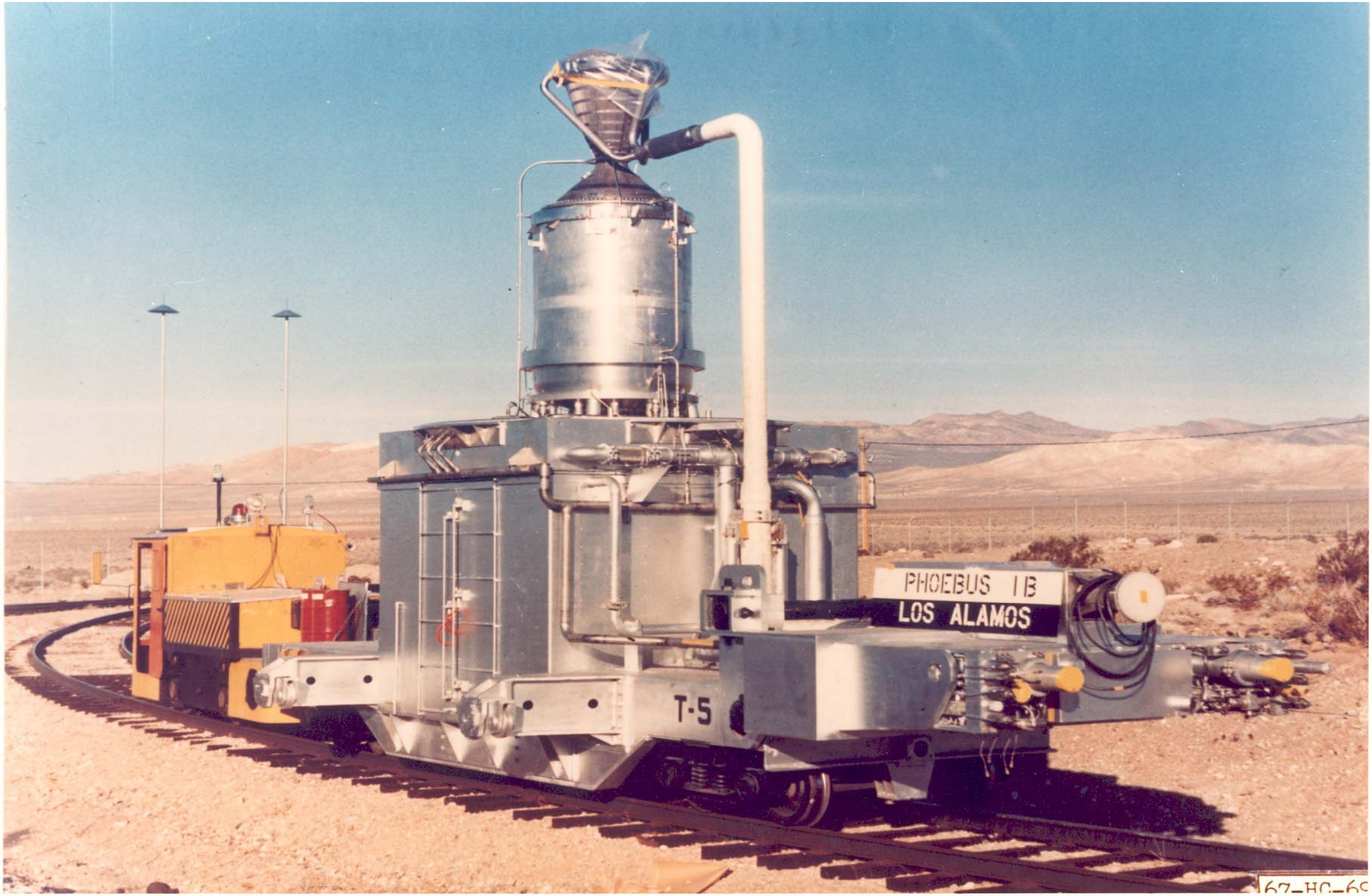
- 20 Rocket/reactors designed, built and tested at cost of ~1.4 B$ (~7.1 B$ today $)
- Engine sizes tested
  - 100, 200, 350, 1100 kN
- H_2 exit temperatures achieved
  - 2,350-2,550 K (Pewee)
- I_{sp} capability
  - 825-850 sec (tested on NERVA-XE)
  - 850-875 sec (chosen for NERVA flight engine)
- Burn duration
  - ~ 62 min (NRX-A6 - single burn)
  - ~ 2 hrs (NRX-XE: 28 burns / accumulated time)
- Engine thrust-to-weight
  - ~3 for 350 kN NERVA
- "Open Air" testing at Nevada Test Site
- Program ended with operating industrial prototype engine "NERVA"



The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

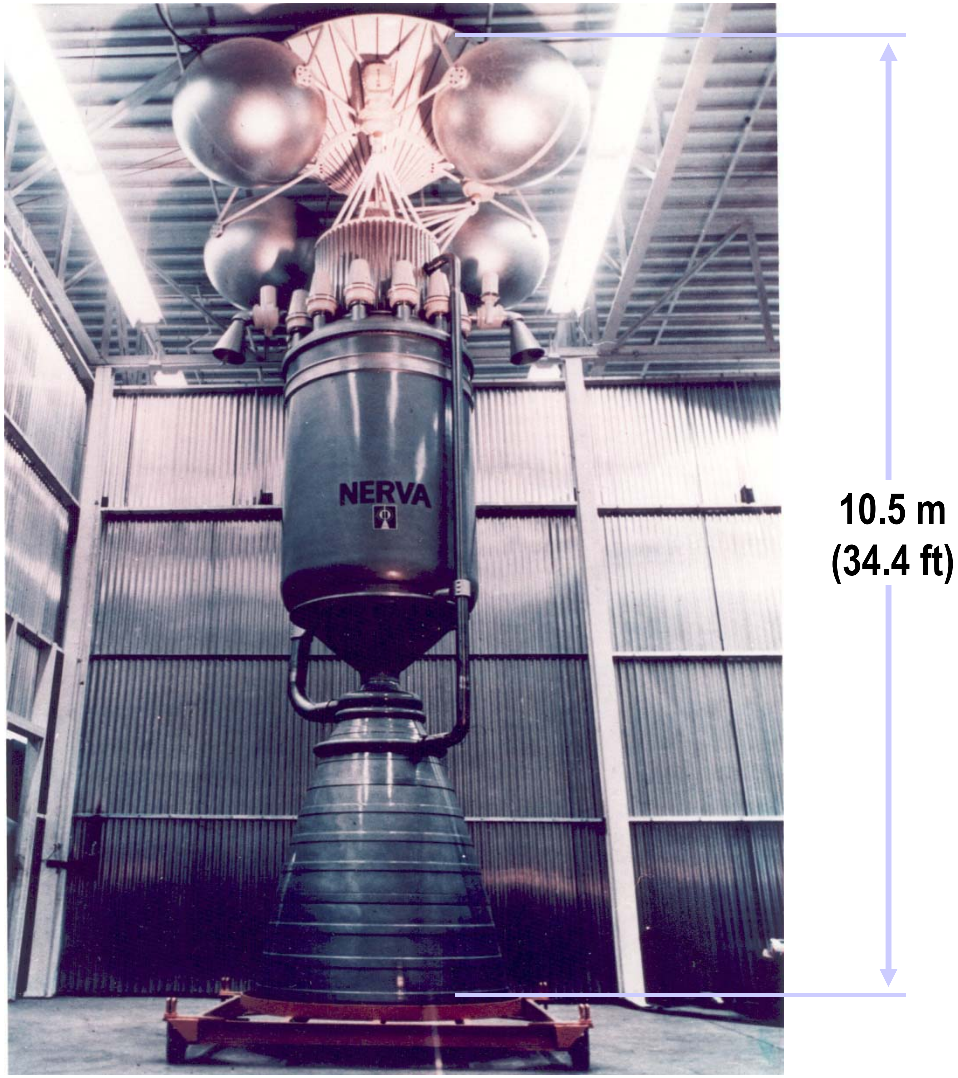
NERVA: Nuclear Engine for Rocket Vehicle Applications

Source: S. Borowski, NASA Glenn Research Center, Cleveland, Ohio



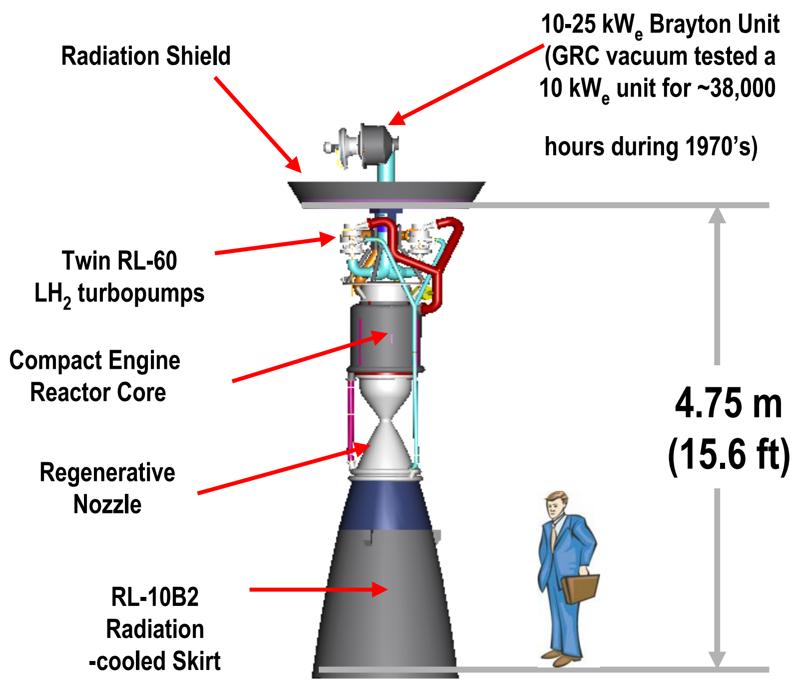
Phoebus-1B Engine Operated at Full Power and Thrust (~1500 MWt, 300 kN) for ~30 min in February 1967

Small NTR Engine Designs for Multi-Mission Use



Small NTR can provide high thrust and Isp plus provide stage electrical power.

Small size compatible with existing chemical rocket hardware; time and cost to develop, ground test and fly is reduced (~12-15 yrs) compared to larger engines



Size of 1972 Vintage 350 kN (75 klb$_f$) NERVA Engine

Source: S. Borowski, NASA Glenn Research Center, Cleveland, Ohio

66 kN (15 klb$_f$) / 25 kW$_e$ "Bimodal" NTR Engine

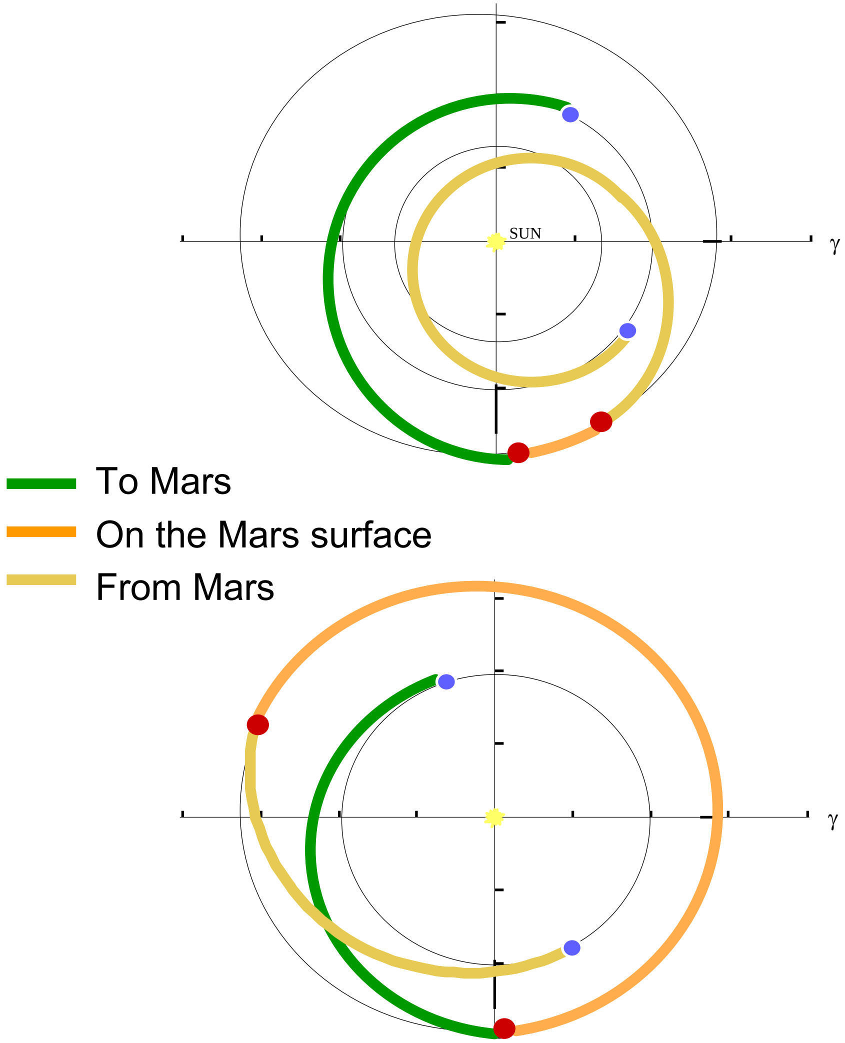
340 MWt / 150 kWt

What about radiation protection?

- In space the radiation doze rates are significantly higher
  - Earth provides important radiation protection with the atmosphere and magnetic field
- For example: 90 day mission to Moon
  (**2 days** in LEO (Low Earth Orbit), **4 days** on route and **84 days** on the Lunar surface, 1 cm Al shield)
- Calculated absorbed dose for this example is 80 mSv
  - Absorbed dose in the case of significant Solar activity is 1,3 Sv
  - Can be reduced to 200 mSv with thicker (4 cm Al) shielding ;-)

2.4 mSv	- natural background in Europe
20 mSv	- annual limitation for exposed
1 Sv	- signs of radiation sickness
3 Sv	- potentially lethal dose
10 Sv	- lethal dose LH_{50}(100 Sv – instant death)

Mission to Mars (chemical fuel)



- ***Opposition-Class Mission Characteristics***
  - Short Mars stay times (typically 30 to 90 days)
  - Relatively short round-trip times (400 to 650 days)
  - Missions always have one short transit leg (either outbound or inbound) and one long transit leg
  - Long transit legs typically include a Venus swingby and a closer approach to the Sun (~ 0.7 AU or less)
  - This class trajectory has higher ΔV requirements

- ***Fast-Conjunction Class Mission Characteristics***
  - Long Mars stay times (500 days or more)
  - Long round trip times (~ 900 days)
  - Short "in-space" transit times (~ 140 to 210 days each way)
  - Closest approach to the Sun is 1 AU
  - This class trajectory has more modest ΔV requirements than opposition missions

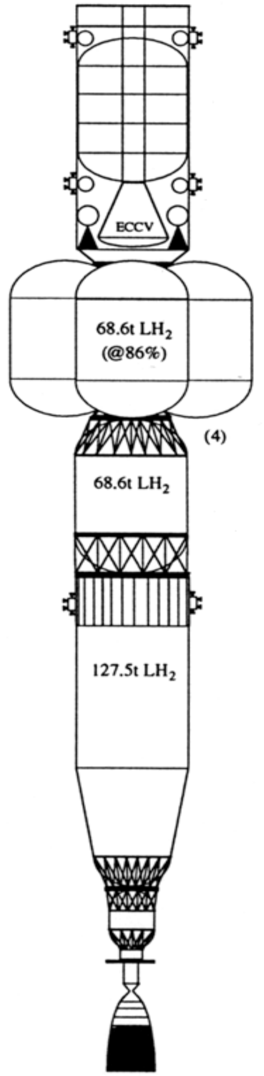
What about radiation protection?

- Human Mars missions are different!
  - Duration 3 years
    (1 year there, 1 year back, 1 year on the surface)
  - Long exposure to Solar events
  - No protection from Earths magnetic field
- Calculated absorbed dose is 1 Sv
  - Without significant Solar activities
  - With shielding (1 cm Al)
  - Significant Solar activities can end with lethal doses to crew

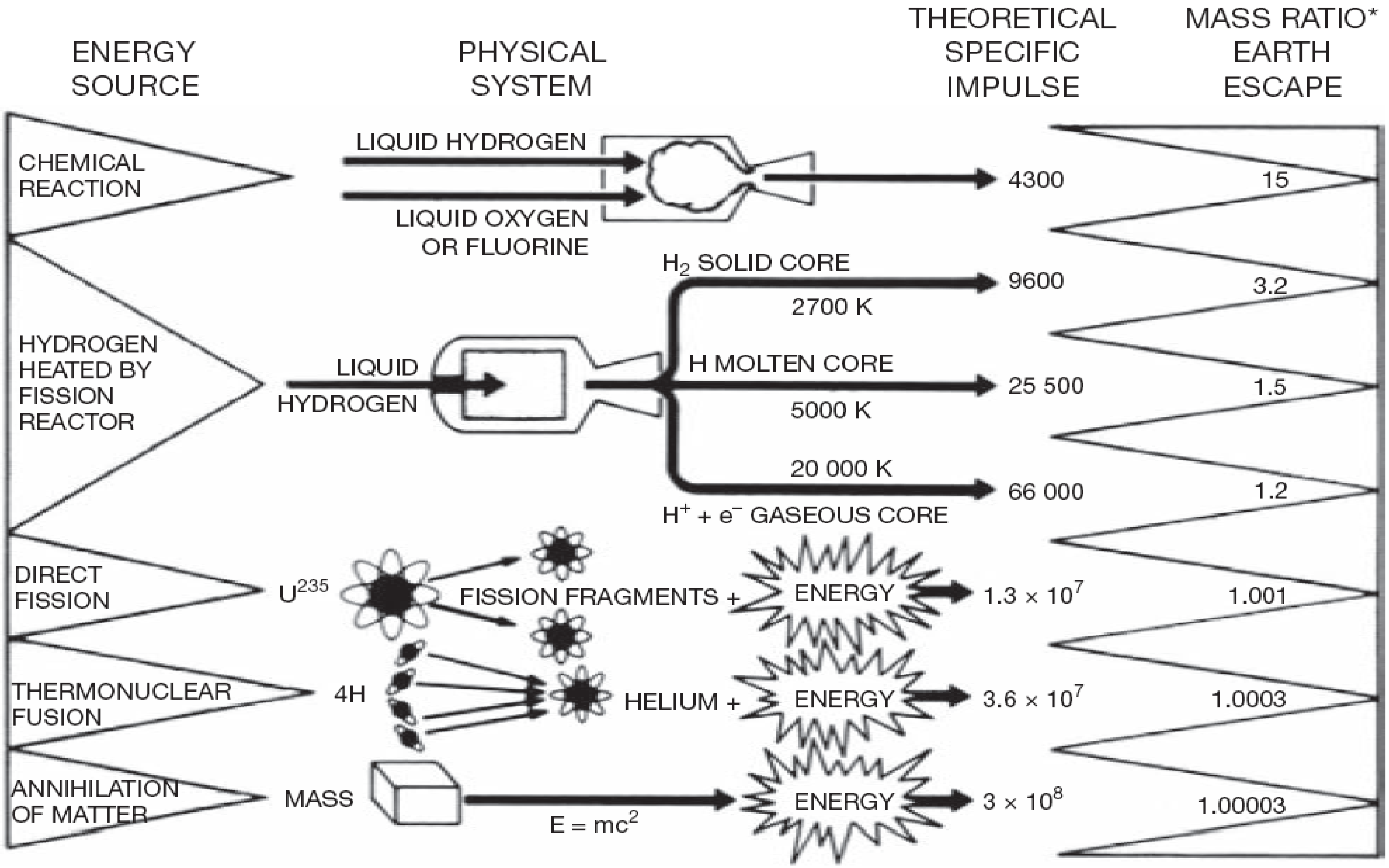
2.4 mSv	- natural background in Europe
20 mSv	- annual limitation for exposed
1 Sv	- signs of radiation sickness
3 Sv	- potentially lethal dose
10 Sv	- lethal dose LH_{50}(100 Sv – instant death)

Radiation protection during BNTR burns

- Using BNTR engines results in higher specific impulse
- Higher specific impulse results in higher travel velocities and shorter travel time
- Crew is protected with LH2 tanks and habitat shielding (there to protect the crew from Solar activities)
- Reactors operates at full power only 4 times
- Calculated additional integral dose to the crew is 5 to 21 mSv
- Higher velocity reduces natural exposure for at least 5 % (~ 150 mSV)



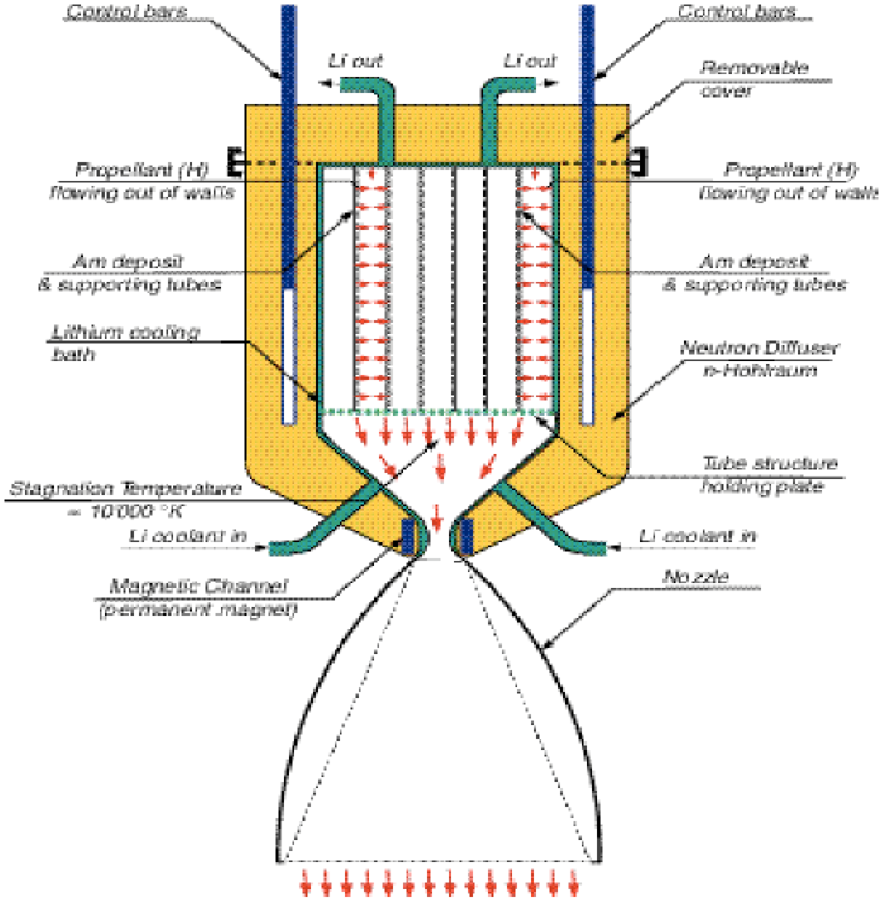
As a Conclusion



*RATIO OF TAKE-OFF TO FINAL MASS

Hydrogen heated by fission fragments

- Hydrogen gas heated by fission fragments
- Heated H used for trust
- T=10 000°K



Thin layer Am-242m reactor concept. (Carlo Rubbia)

Thank you for your attention!

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Literature

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